

# $Z^0$ -tagged quark jets at the large hadron collider

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**Abstract** The Large Hadron Collider will allow studies of hard probes in nucleus-nucleus collisions which were not accessible at the Relativistic Heavy Ion Collider—even the study of small cross-section  $Z^0$ -tagged jets becomes possible. Going beyond the measurement of back-to-back correlations of two strongly interacting particles to measure plasma properties, we replace one side by an electromagnetic probe which propagates through the plasma undisturbed and therefore provides a measurement of the energy of the initial hard scattering. We show that at sufficiently high transverse momentum the  $Z^0$ -tagged jets originate predominately from the fragmentation of quarks and anti-quarks while gluon jets are suppressed. We propose to use lepton-pair tagged jets to study medium-induced partonic energy loss and to measure in-medium parton fragmentation functions to determine the opacity of the quark gluon plasma.

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## 1 Introduction

The quantitative study of the properties of the quark gluon plasma is a major thrust of the heavy-ion program at the Large Hadron Collider (LHC), with dijet studies being an important tool. Analyses of the suppressed production of hadrons from dijets at the Relativistic Heavy Ion Collider (RHIC) have provided the main evidence that the quark-gluon plasma has been produced. However, this observable has severe inherent limitations. For example, the inclusive measurements at RHIC do not allow for the determination of the initial jet energy and, consequently, the inferred jet energy loss is ambiguous. This results in a staggering order of magnitude uncertainty in the extraction of certain QGP properties [1].

In the following we study a dijet channel that becomes experimentally accessible only at the LHC: high transverse momentum  $Z^0$ -bosons in association with hadronic jets [2, 3]. The production channels are  $gq \rightarrow Z^0q$ ,  $g\bar{q} \rightarrow Z^0\bar{q}$  and  $q\bar{q} \rightarrow Z^0g$  ( $q\bar{q}$  annihilation) with the subsequent  $Z^0$  decay,  $Z^0 \rightarrow l^+l^-$  ( $l = e, \mu$ ), and parton fragmentation,  $q/\bar{q}/g \rightarrow \text{jet}$ . The reconstructed momentum of the  $Z^0$  gives direct access to the initial momentum of the opposite-side jet, since leptons interact weakly with the medium. This allows for a direct measurement of an in-medium fragmentation function in heavy ion collisions. The comparison of these fragmentation functions to the p-p case allow for a direct and precise partonic energy loss measurement. Another important aspect of using the  $Z^0$ -tag is that there is no surface bias as there is in the case of triggering on leading hadrons. The  $Z^0$ -tagged initial scatter originates from anywhere inside the overlap volume for the electromagnetic tag does not interact with the plasma.

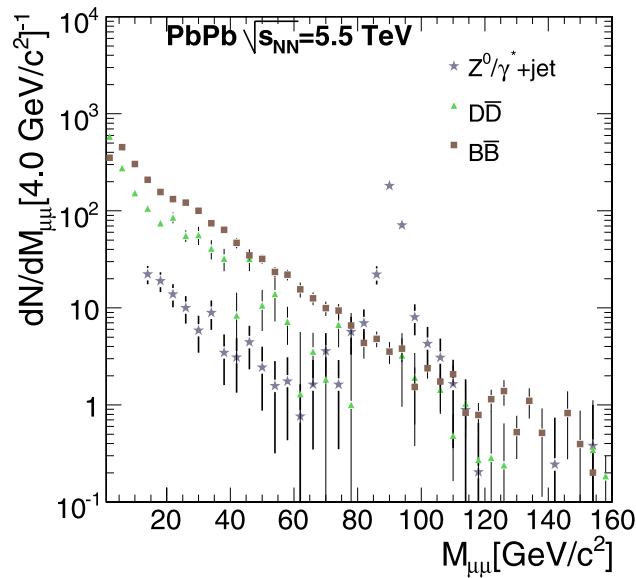
## 2 $Z^0$ -jet production

We consider Pb+Pb collisions at  $\sqrt{s_{NN}} = 5.5$  TeV for a nominal year of heavy ion running at LHC. The  $Z^0$  + jet rate in Pb+Pb collisions is obtained from  $A^2$ -scaled  $pp$  cross sections, evaluated with PYTHIA 6.32 [4] (CTEQ5M PDFs, simulation details can be found in [5]). We have selected dimuons from virtual photon and  $Z^0 \rightarrow \mu^+\mu^-$  decays [6] with momentum and pseudorapidity of  $p_T^\mu > 3.5$  GeV/c and  $|\eta^\mu| < 2.4$ . These cuts reflect a typical acceptance of the LHC experiments. The results [7] of the PYTHIA simulations are presented by the star symbols in Fig. 2.1, which shows the invariant mass distribution for dimuons. The  $Z^0$  peak clearly dominates the spectrum and is experimentally easy to isolate.

## 3 Dimuons from heavy quark decays

Heavy meson pairs produced by gluon splitting are the major source of correlated dimuons and their kinematics is very

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**Fig. 2.1** Invariant Mass Distribution for dimuons above a transverse momentum of the dimuon of 25 GeV/c

similar to that of the signal. Here we only discuss this heavy flavor background, other background sources, e.g. hadrons misidentified as muons, are the subject of further studies.

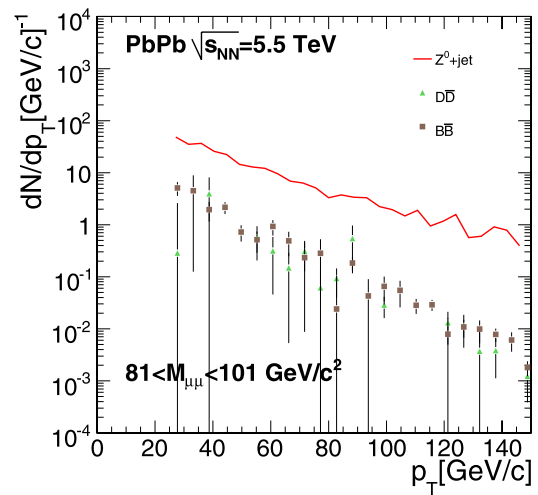
A heavy meson pair can produce a dimuon through  $D\bar{D}/B\bar{B} \rightarrow \mu^+\mu^- + X$ . In order to estimate this effect, we have used, motivated by previous studies [8], the NLO HVQMNR [9] (details of the simulations can be found in [5]). We show in Fig. 2.1 the result of these calculations: the dimuons from  $D\bar{D}$  are shown as triangles, dimuons from  $B\bar{B}$  are shown as square symbols. For invariant masses below the  $Z^0$  peak these dimuons dominate the spectrum.

#### 4 $Z^0$ -tagging of jets

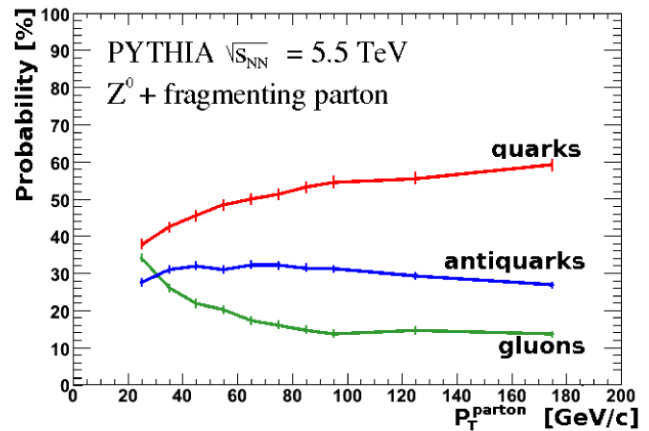
In order to evaluate the feasibility of  $Z^0$ -tagging of jets (the signal), we isolate the  $Z^0$  via an invariant mass cut and investigate the rates of background dimuons from heavy meson decay [7]. Figure 4.1 shows the signal and background rates as a function of the dimuon transverse momentum distribution  $p_T^{\mu\mu}$  in the mass window where the  $Z^0$  peak dominates: 81–101 GeV/c<sup>2</sup>. The  $Z^0$  signal is well above the  $D\bar{D}$  and  $B\bar{B}$  background for the entire  $p_T^{\mu\mu}$  range. In experiments with vertex tracking, the background can be further reduced (factor 5–10) by requiring that the dimuon originates at the primary vertex, since dimuons from semileptonic decays have displaced vertices.

#### 5 Selecting quark jets

The initial hard scattering of partons determines whether the  $Z^0$ -tagged jet is a quark or gluon jet. The  $x$ -range

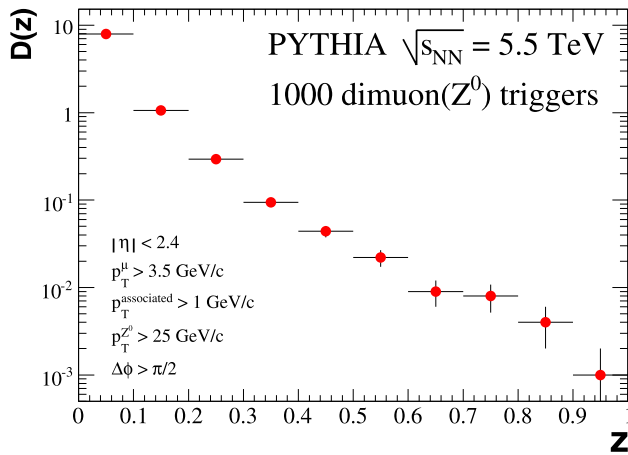


**Fig. 4.1**  $Z^0$ -tagged jets (line) and background dimuons from heavy meson decay as function of the transverse momentum of the dimuons



**Fig. 5.1** Fragmenting parton probability for  $Z^0$ -tagged jets as function of the transverse momentum

( $\approx 0.05$ ) for back-to-back scattering at a transverse momentum of 100 GeV/c at mid-rapidity in heavy-ion collisions at  $\sqrt{s_{NN}} = 5.5$  TeV favors quarks over anti-quarks by a factor 2 to 3. The final state with a gluon opposing the  $Z^0$  is therefore less probable. Figure 5.1 shows the probability for quarks, anti-quarks and gluons opposite to the  $Z^0$  as function of the transverse momentum. While the contributions are roughly equal at a transverse momentum of 25 GeV/c at higher momenta quarks have the highest probability, anti-quarks are about a factor two lower and gluons have the smallest probability.  $Z^0$  tagging at sufficiently high transverse momentum therefore selects predominately quark/anti-quark jets. This eases the theoretical interpretation of measured fragmentation functions via partonic energy loss calculations.



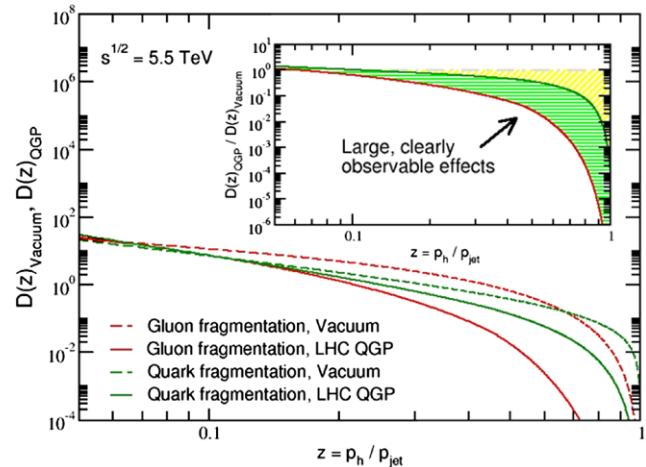
**Fig. 6.1** Fragmentation Function  $D(z)$  as determined from the reconstruction of correlated hadrons. The statistical error bars reflect a year-one measurement

## 6 Measurement of fragmentation functions

The knowledge of the jet momentum in  $Z^0$ -tagging allows for the determination of the fractional momentum  $z = p_T^{\text{assoc}}/p_T^{\text{trig}}$  of hadrons associated with the jet (as measured in a tracking detector) and therefore the construction of a fragmentation function.

In order to estimate the statistical significance of a “year-one” measurement, 1000 PYTHIA dimuon triggers were generated (see [5]). The yield  $Y_{\text{away}}$  of away-side jet hadrons, selected via their azimuthal correlation to the tag (see [5]), is analyzed as a function of the momentum fraction. The  $D(z) = (1/N_{\text{trig}})(dY_{\text{away}}/dz|_{p_T^{\text{trig}}})$  distribution (Fig. 6.1) contains all hadronic fragments of the initial parton, including the hadrons from the fragmentation of gluon radiation of the parton, plus, in the case of nucleus-nucleus collisions, the hadrons from the underlying event. While the figure illustrates the principle of the measurement for p-p collisions, the same procedure will, for Pb-Pb collisions, result in the measurement of the in-medium fragmentation function  $D(z)$ .

The publication [10] by I. Vitev presents GLV calculations on nuclear effects on inclusive hadron production in heavy ion collisions. The paper discusses in (21) the modification of the fragmentation function in Pb-Pb collisions due to the kinematic modification of the momentum fraction plus the redistribution of energy due to medium-induced gluon bremsstrahlung. Figure 6.2 [11] shows the numerical evaluation of this equation to illustrate the difference between vacuum fragmentation and fragmentation in a QGP created at LHC at 5.5 TeV. The green lines show the effect on the quark fragmentation function, the effect is more pronounced for gluons (yellow lines) because of their stronger coupling to the plasma. The insert shows the ratio of fragmentation functions for the QGP to vacuum case. The quark



**Fig. 6.2** Fragmentation Function  $D(z)$  for quarks and gluons in the vacuum and in a LHC QGP. The fragmentation results for the vacuum case are represented as dashed lines, the QGP result is shown as solid lines. The insert shows the ratio of the fragmentation functions for QGP vs. vacuum. Please note the logarithmic representation

fragmentation functions show, e.g. at a momentum fraction  $z$  of 0.7 a suppression of about a factor 5. We conclude from the comparison of these predictions with the year-one statistics, shown in Fig. 5.1, that the measurement should be feasible.

## 7 Conclusions

We have presented a study for measuring in-medium fragmentation functions via  $Z^0$ -tagged jets in heavy-ion collisions at the LHC. The signal rates of  $Z^0(\rightarrow \mu\mu) + \text{jet}$  were computed with PYTHIA. The heavy meson semileptonic background,  $D\bar{D}/B\bar{B} \rightarrow \mu\mu$ , was calculated at NLO with the HVQMNR code. We demonstrate that the  $Z^0$ -tag selects predominantly quark/anti-quark jets at sufficiently high transverse momenta. Kinematical studies of both signal and background show that a measurement of dimuon-tagged jets in Pb+Pb collisions at the LHC is feasible.

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